# STTR Phase-I

# Final Report

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**14. ABSTRACT**

Testing of a high-resolution decision feedback equalizing with parallel tracking of large Doppler algorithm developed at FAU by Prof. Beaujean: The long-term objective is the commercialization of a high-speed high-frequency acoustic modem transmitting data at true rates of up to 105,000 bps, at a maximum range of 500 m and operate between 240 kHz and 380 kHz. Acoustic communications were achieved at a coded rate up to 150,000 bps at a range of 50 m. At 75 m, acoustic communications was possible up to 50,000 bps (coded), due to limitations of the source power amplifier. Accurate Doppler correction and sufficient SNR were required to perform broadband underwater acoustic communications at high frequencies. Results observed at 75 m under adverse conditions in terms of Doppler and SNR (4 dB) indicated that the BPSK modulation still provides acceptable results using 20 μs and 40 μs symbols. The results were obtained using an output power of 0.63 W, which showed that the modem was remarkably power efficient and ideal for small UUVs and divers, as it achieves 130,692 bits/J at 150,000 (coded) bps.

**15. SUBJECT TERMS**

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Through this report, the High-Speed High-Frequency Broadband Acoustic Modem will be referred to as the HS-HFAM. References to the first report [8] and second report [9] are used through the report to keep the overall document concise.

## 1. Scientific and Technical Objectives

This phase-I work addresses the following two areas of interest:
- Development of improved algorithms for estimating the time-varying impulse response of the ocean in rapidly fluctuating environments.
- Development of the means to exploit the temporal, frequency, spatial, and bearing diversity of acoustic channels.

The specific objectives of this first phase are:
- The implementation, modification and troubleshooting of the proposed algorithm for high-speed high-frequency acoustic communications using an electronic setup already available at FAU. Only the most fundamental aspects of the algorithm would be implemented and tested. For example, canned information would be transmitted from the source to the receiver.
- Preliminary testing and evaluation of the technique to determine bit rate feasibility in ports and very shallow waters.
- A final report for this Phase-I proposal.

The questions to be answered are:
- Can a bit rate-range product of 50 kbps-km or more be achieved?
- What is the efficiency in bits/Joule of this system?
- What is the frame error rate, or number of non-recovered messages, over the course of minutes, hours and days as a function of range, rate and environmental conditions?
- If proved to work, can this device be in the form of a small, low-power package compatible with modern autonomous underwater vehicles?

## 2. Approach

An experimental approach is chosen to prove that the HS-HFAM concept is feasible and that adequate performance can be achieved. Figure 1 shows a diagram of the experimental setup. The reader can refer to the two progress reports for pictures of the equipment [8][9]. The source, composed of an FAU-designed low-power DSP board coupled with a broadband power amplifier and a COTS ITC-1089D transducer is currently installed in a water-tight case. The receiver unit uses technology developed in collaboration with EdgeTech for an ONR-sponsored, mine-countermeasures project lead by Dr. Steve Schock. Canned information is transmitted from the source to the receiver. The receiver decoding software is derived from previous work in underwater acoustic communications by Dr. Beaujean [1-7].

The HS-HFAM transmits messages as described in [9]. Three distinct parts in each message are used to detect, synchronize and to provide basic information about the data being sent and to transfer encoded data itself. Each packet contains a sparse training and error coded, parity-coded

and interleaved binary sequence. The packets are demodulated using a Doppler-compensated DFE process, de-interleaved, error-decoded and parity-checked. Each packet is comprised of three different aspects that help ensure efficient, error-free reception of the data. A 2.7 ms chirp is transmitted between 262.5 and 337.5 kHz, with a "dead-time" of 4 ms, and serves to synchronize the data being sent. The planned Frequency Hopped Spread Spectrum sequence described in the previous report is not available at the present time.

The second portion of the message contains the message "header" information which sends basic information about the data being sent. Within the header there are three distinct preambles. The first preamble informs the receiver whether there is an acknowledge request, what the symbol length is set to (40 µs, 20 µs, 13.3 µs), whether BPSK or QPSK is being used, if the message is a retry and finally sets the power level to be used. The contents of preamble two include the number of packets which are being sent and the number of information bytes in trail on top of the number of 32-bits data words provided in preamble three. Finally, preamble three carries the number of non-coded complete data words (32 bits) in trail. Each preamble is 5.1 ms in length and includes 3 ms dead-time between them.

The last portion contains the actual data being sent, with a short training sequence at the beginning. This segment of the message comprises the bulk of the information sent. This sequence is partitioned into frames, which last 28.1 ms in the fastest mode and up to 51 ms in the slowest mode. 256 training symbols are sent for each packet, no matter what the modulation is. Following the training sequence, the message will be encoded using a 16-bit Cyclic Redundancy Check (CRC) and BCH code.

The receiver decoding software consists of an efficient lattice-structured decision-feedback equalizer combined with a Doppler tracking process and error coding, capable of processing the recorded data in real-time [6-9].

A series of experiments has been performed:
1. Using direct cable connection between the source and the receiver [9].
2. In the test tank (1.5m x 1.5m x 2m) [9] with minimal amount of noise, and a reverberation time of approximately 5 ms.
3. In the marina facing FAU SeaTech, keeping source and receiver static at 20 to 50 m range [9], with a water depth of 1 m. Limited motion of the source is allowed.
4. In the Port Everglades turning basin experiments at ranges from 20 m to 80 m. Both source and receiver can move.

In each case, the ambient noise level, bathymetry, channel impulse response, reverberation time, Doppler shift and Doppler spread are measured over several hours of transmission. The source level, bit error rate and information data rate are also measured. From these experiments, the bit rate-range (kbps-km) product and efficiency (bits/Joule) and the bit error rate, over the course of minutes, hours and days is estimated.
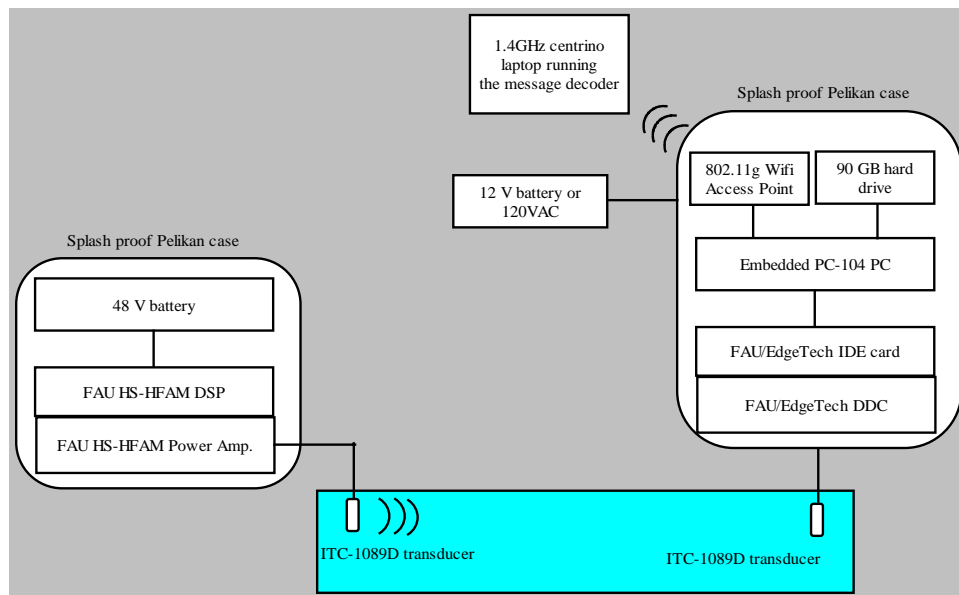
Figure 1. System diagram of the high-frequency acoustic communication setup.

## 3. Work Completed

The specific objectives of this research were:
- The implementation, modification and troubleshooting of the proposed algorithm for high-speed high-frequency acoustic communications using an electronic setup already available at FAU. Only the most fundamental aspects of the algorithm would be implemented and tested. Canned information would be transmitted from the source to the receiver.
- Preliminary testing and evaluation of the technique to determine bit rate feasibility in ports and very shallow waters.
- A final report for this Phase-I proposal.

During the phase-I period (August 1st 2005 to February 3rd 2006), the following milestones were achieved:
- Electronics accomplishments:
  - o The components of the acquisition system prototype (digital down-converter card, IDE interface FPGA card), built and tested at FAU [8].
  - o Broadband power amplifier was built and tested at FAU [8].
  - o Packaged acquisition system and associated acquisition software supplied by EdgeTech to FAU [9].
- Software accomplishments:
  - o Stable software was ported to the source DSP board, which has been programmed to generate canned acoustic images, or images coming from an external user through the Ethernet port [8][9].
  - o A receiver software capable of processing the recorded data in real-time, and to record the transmissions, developed at FAU [8][9]. An efficient lattice-structured decision-feedback equalizer combined with a Doppler tracking process and error coding constitute the core of the process.

- Experimental accomplishments:
    - o Testing of the HS-HFAM hardware using direct (cable) connection between the source and the receiver in October 2005 [8].
    - o Testing of the HS-HFAM hardware in a tank located at FAU, November 2005 [9].
    - o FAU SeaTech marina experiments at ranges from 20 m to 50 m [9]. These tests took place in December 2005 and January 2006. The source was either still or moving at a top speed of 1 m/s. The latest results, not presented in [9], are covered in this final report. Overall, acoustic communications were made possible at a rate up to 150,000 bps (coded) at a range of 50 m. The water depth varied between 1 and 2 m.
    - o Port Everglades turning basin experiments at ranges from 20 m to 80 m, in January 2006. Both source and receiver were moving at a top relative speed of approximately 1.5 m/s. The results, not presented in [9], are covered in this final report. Again, acoustic communications were made possible at a rate up to 150,000 bps (coded) at a range of 50 m. At 75 m, acoustic communications was still possible up to 75,000 bps (coded), due to limitations of the source power amplifier. The water depth varied between 13 and 15 m.
- Administrative accomplishments:
    - o Two progress reports have been submitted in September and December 2005 [8][9].
    - o A final report and phase-II work plan have been submitted in early February 2006.

Therefore, all the objectives of this proposal have been met.


## 4. Positive and Negative Results

### *4.1. Evaluation method*

An experimental approach is chosen to prove that the HS-HFAM concept is feasible and that adequate performance can be achieved. The implementation and testing of the algorithm for high-speed high-frequency acoustic communications is based on technology and equipment already available at FAU and EdgeTech. The technology is presented in details in the previous reports [8][9]. Figure 1 summarizes the experimental setup.

The acoustic source transmits a known sequence of messages at various speeds, based on the modulation (BPSK and QPSK) and bandwidth (13µs to 40 µs). Table 1 summarizes the message specifications during the tests performed in January 2006. Examples of transmitted images are shown in Figure 2. Examples of transmitted and received images are available for comparison in Figures 18 and 19. The source and receiver location and speed are known, as well as the bathymetry of the transect between source and receiver. Both source and receiver use calibrated ITC-1089D transducers. The source level is known (173 dB re 1µPa at 1m). The receiver unit provides the following real-time information regarding the system and the environment:

1. Impulse response on a message packet basis (every 10 ms at best), estimated between 262.5 kHz and 337.5 kHz.
2. Doppler shift and spread through an auto-regressive PSD estimate of a continuously transmitted tone (375 kHz).
3. Noise PSD between 225 kHz and 375 kHz.
4. SNR in the 262.5 kHz and 337.5 kHz band.

5. Bit error rate associated with each packet and message.  Please refer to [9] for the message format.



Figure 2.  43008-bit JPEG image transmitted during the earlier tests (November and December 2005, left), 8192-bit PGM image transmitted during the latest tests (January 2006, right).

| Modulation Type | BPSK | BPSK | BPSK | QPSK | QPSK | QPSK |
|---|---|---|---|---|---|---|
| Symbol Duration | 40 µs | 20 µs | 13 µs | 40 µs | 20 µs | 13 µs |
| Symbol Bandwidth | 25 kHz | 50 kHz | 75 kHz | 25 kHz | 50 kHz | 75 kHz |
| | | | | | | |
| No. of Messages | 13 | 8 | 5 | 8 | 5 | 5 |
| Information bits/ frame | 672 | 1056 | 1760 | 1056 | 1760 | 1760 |
| Frame duration (ms) | 51 | 35.7 | 38 | 40.8 | 30.3 | 20.2 |
| Image binary size (bits) | 8192 | 8192 | 8192 | 8192 | 8192 | 8192 |
| Message duration (s) | 0.7291 | 0.3367 | 0.2321 | 0.3775 | 0.1936 | 0.1431 |
| Message duration without trigger and header (s) | 0.699 | 0.3066 | 0.202 | 0.3474 | 0.1635 | 0.113 |
| | | | | | | |
| Information rate (bps) | 11235 | 24330 | 35295 | 21700 | 42314 | 57246 |
| Information rate without trigger and header (bps) | 11719 | 26718 | 40554 | 23580 | 50103 | 72495 |
| Information rate per packet (bps) | 13176 | 29579 | 46315 | 25882 | 58085 | 87128 |
| Coded rate (bps) | 25000 | 50000 | 75000 | 50000 | 100000 | 150000 |

Table 1.  Message specifications for each modulation under the HS-HFAM configuration used in January 2006.


## 4.2. Analyses Conducted

The final report focuses on the experiments conducted in January 2006, which lead to a significant breakthrough in the modem results.  The analysis of the experimental results obtained in October through December is given in [9].  Two major series of experiments were conducted:
1. Very shallow water measurements (1 to 2 m of water depth) in the noisy environment of the FAU SeaTech marina, with relatively slow motion of the target.
2. Shallow water measurements (13 to 15 m of water depth) in the south turning basin of Port Everglades, allowing for longer range and higher relative speed.


### 4.2.1. FAU SeaTech marina experiments

The experimental setup in the SeaTech marina is presented in Figure 3.  The receiver is placed on the dock, at 1.5 m from a concrete wall, between wood pilings.  The source is placed on the back of a kayak, moving at speeds up to 1 m/s.  Due to the limited space however, relative motion was typically of the order of 0.25 to 0.5 m/s.  Both source and receiver are placed 0.5 m below the surface.  The range between source and receiver varied from 25 m to 50 m.  The

reader can also refer to [9] for results obtained under static conditions of both source and receiver, and for bathymetry information regarding the marina.



Figure 3. Sky and side view of the SeaTech marina, indicating the source and receiver locations (25 and 50 m ranges) during the experiments of January 2006.

Data are collected over the course of several hours, a message being transmitted every two seconds. The shear number of messages and data collected (tens of gigabytes) does not allow for a detailed study of the environment for each message. Instead, relevant information of the acoustic environment are shown in the form of the impulse response of the acoustic channel when the source is located at 50 m from the receiver, SeaTech Marina, January 24th 2006 (Figure 4). Real-time measurement of the Doppler spread (Figure 5) and background noise (Figure 6) is also shown.

Figure 4 indicates that the reverberation is only benign in this type of environment and at these frequencies. Measurements in the marina and the turning basin confirmed this statement. Overall, the reverberation time tends to remain within 1 ms, and very occasionally reaches 2 ms. This observation can be directly tied to the loss of coherence of the scattered sound. Again, these tests took place in the proximity of boat hulls, concrete wall and shallow water, which constitute a highly reverberant environment. Therefore, the use of broadband, high-frequency signals not only limit the background noise level as shown in Figure 6 (typically associated with thermal noise), but also the amount of coherent inter-symbol interference (ISI) due to sound reverberation.

Unfortunately, these advantages come at a price: Doppler shift and spread. As shown in Figure 6, even when the source is in slow motion, 50 Hz of Doppler shift and as much Doppler spread is observed at 375 kHz. These observations become even more apparent in the second set of experiments (turning basin) presented in this section. Doppler and SNR are the two limiting factors in the overall performance of the communications system. The performance of the communication system during this set of experiments is summarized in Table 2, located in the findings section (4.3). More results are also available in [9]. A more refined analysis of the performance of the communications system is shown in Figures 7 through 9, during the transmission of 110 messages. Each Figure shows the bit error rate (BER) for each message, defined as the ratio of erroneous information bits received (after error coding) to the total number of information bits, plotted against time. Note that the SNR shown in these Figures was measured using the message trigger [9]. SNR and peak Doppler shift measurements are overimposed on the BER plots. Although the Doppler is fairly limited during the marina test,

small drops in performance appear as the SNR becomes too low and/or the Doppler becomes larger. The transmissions using 40 µs symbols, 20 µs symbols and 13 µs symbols are covered in Figures 7, 8 and 9 respectively.

SNR is mainly a matter of adjusting the source level accordingly. As mentioned in [9], an omni-directional source of 173 dB (0.63 W of acoustic power) is used during these tests. The long term objective is to use a more powerful source amplifier combined with a better suited transducer. Doppler, on the other hand, can only be compensated for by the combination of the built-in Doppler tracking algorithm and Decision Feedback Equalizer (DFE). The DFE also handles ISI. Observations of Figures 7 through 9, as well as Table 2, show that the decoder handles the fluctuations of SNR and Doppler very well indeed: when 20 µs symbols are transmitted using QPSK, which corresponds to a coded rate of 100,000 bps, the BER does not exceed 0.5% (see Figure 8, right plot), except for one message with a BER of 52%. A more careful study indicates that this error is due to a sudden increase in Doppler shift to 110 Hz, associated with the motion of the source, which was not estimated properly by the decoder.

Overall, Figures 7 to 9 indicate that the link remains extremely reliable despite the fluctuations in Doppler and in SNR. The results at the fastest data rate (Figure 9, right) must be used with caution: due to a software issue at the source, only a small fraction of the 13µs-QPSK messages were transmitted, which explains the limited number of messages received. This problem has now been resolved.
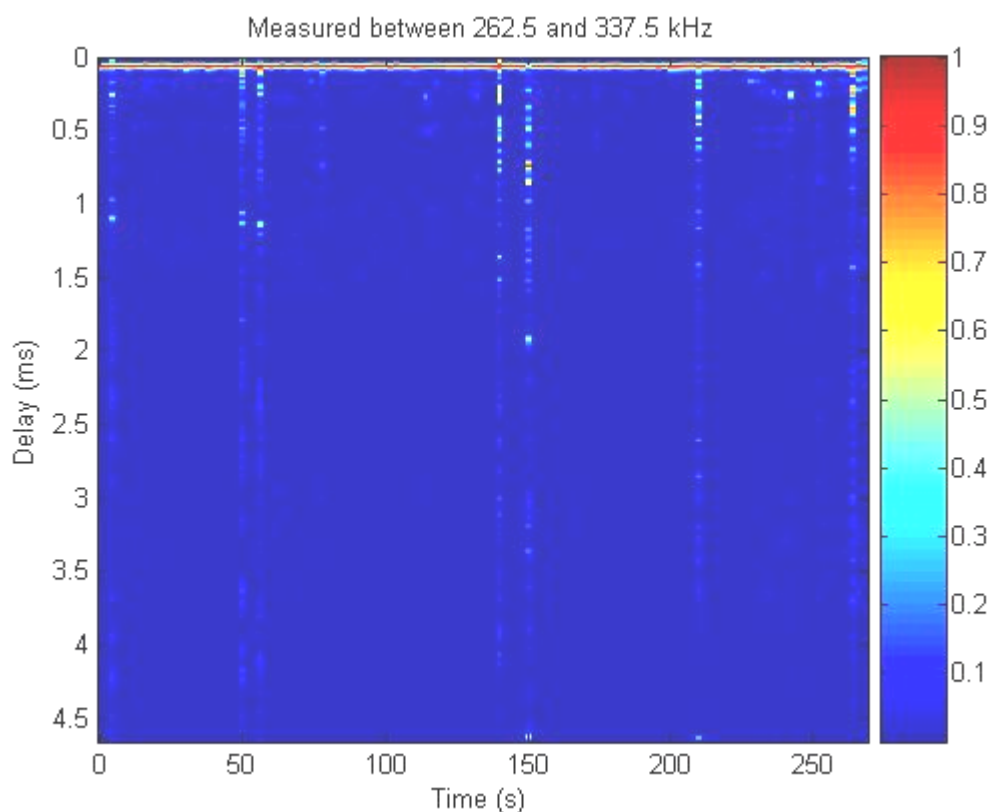


Figure 4. Impulse response of the acoustic channel when the source is located at 50 m from the receiver, SeaTech Marina, January 24th 2006.
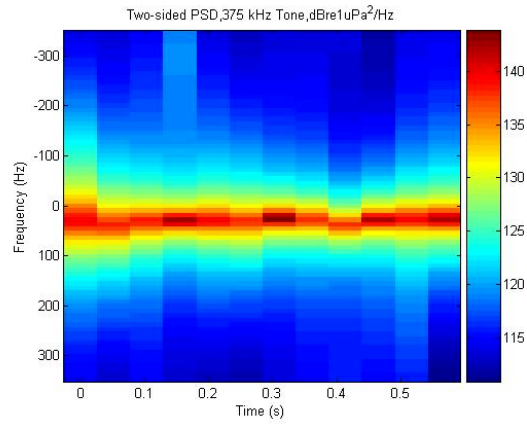
Figure 5. Real-time measurement of the Doppler spread during the transmission of a 25kHz-BPSK modulated message; the source is located at 50 m from the receiver, SeaTech Marina, January 24<sup>th</sup> 2006.
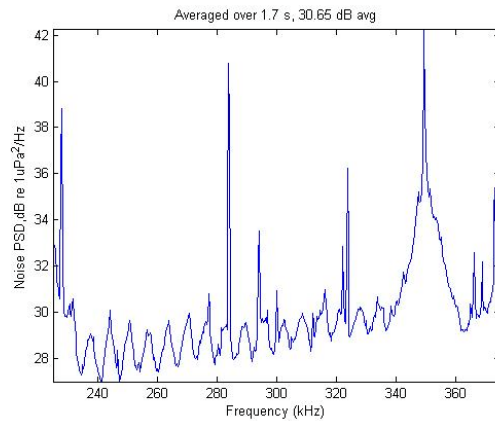


Figure 6. Background noise measurement while the source is located at 50 m from the receiver, SeaTech Marina, January 24<sup>th</sup> 2006.
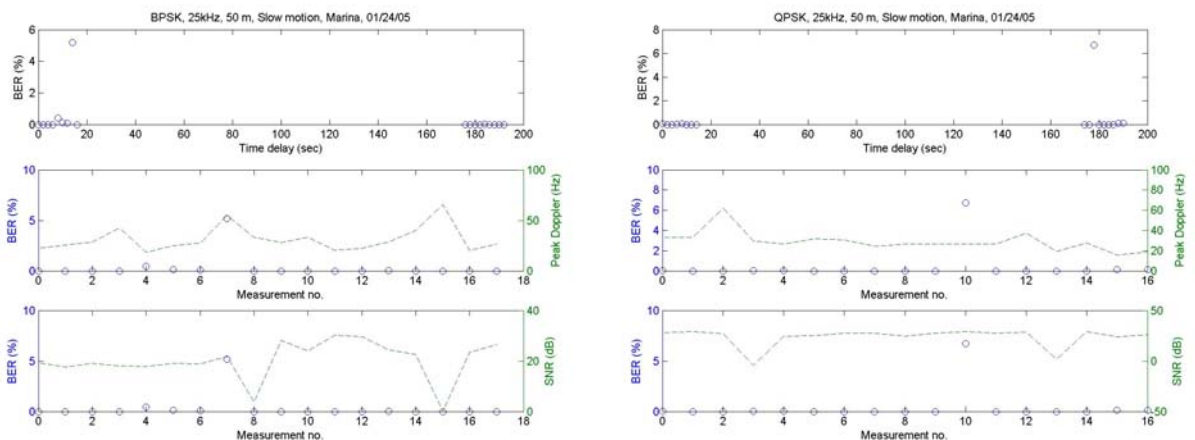


Figure 7. Performance review for messages using 40 µs symbols (BPSK and QPSK), when the source is located at 50 m from the receiver, SeaTech Marina, January 24<sup>th</sup> 2006.

Figure 8.  Performance review for messages using 20 µs symbols (BPSK and QPSK), when the source is located at 50 m from the receiver, SeaTech Marina, January 24th 2006.
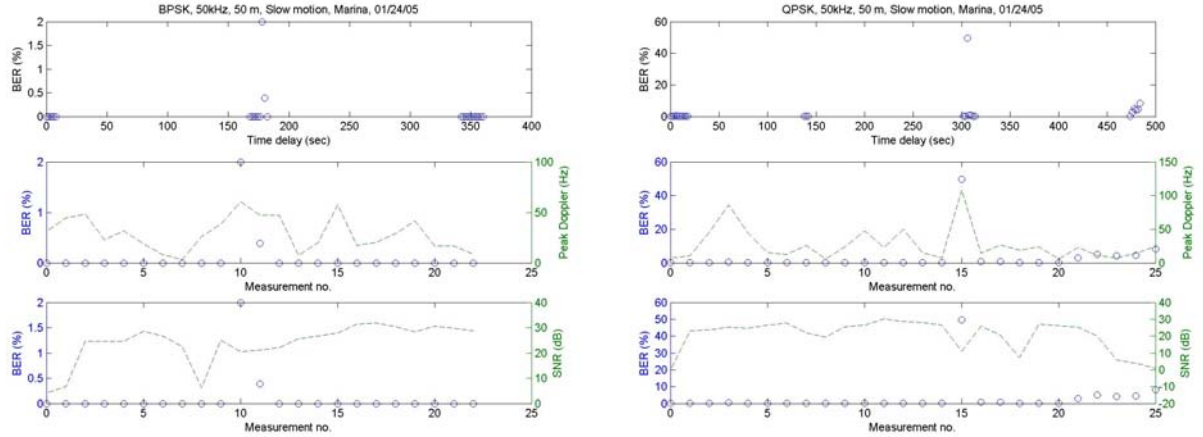


Figure 9.  Performance review for messages using 13 µs symbols (BPSK and QPSK), when the source is located at 50 m from the receiver, SeaTech Marina, January 24th 2006.

### 4.2.2.  Port Everglades south turning basin experiments

The experimental setup in the Port Everglades turning basin is presented in Figures 10 and 11. The receiver is placed on the stern of the Oceaneer IV research vessel.  The source is placed on the back of a kayak, moving at speeds up to 1.5 m/s.  Both source and receiver are placed 0.5 m below the surface.  The range between source and receiver varied from 20 m to 80 m.

Data was collected over the course of two hours, a message being transmitted every two seconds. Again, the shear number of messages and data collected does not allow for a detailed study of the environment for each message.  Instead, relevant information of the acoustic environment is shown in the form of the impulse response of the acoustic channel when the source is located at 50 m from the receiver (Figure 12).  Real-time measurement of the Doppler spread (Figure 13) and background noise (Figure 14) is also shown.

As in the marina, Figure 12 indicates that the reverberation is only benign in this type of environment and at these frequencies. Comparison between Figures 5 and 13 indicate that the background noise PSD remains essentially the same. The most significant difference between the marina and basin experiments holds in range and Doppler. Figure 13 shows that the Doppler shift (measured at 375 kHz) can vary by more than 100 Hz within 0.5 seconds, while Doppler spread commonly exceeds 50 Hz. Again, Doppler and SNR are the two limiting factors in the overall performance of the communications system. The performance of the communication system during this set of experiments is summarized in Table 3, located in the findings section (4.3). Peak Doppler shift were measured up to 300 Hz during this set of experiments.

A more refined analysis of the performance of the communications system is shown in Figures 15 through 17, during the transmission of 103 messages. SNR and peak Doppler shift measurement are overimposed on the BER plots. Again, the fluctuations of Doppler and SNR are the dominant factors determining overall system performance. The transmissions using 40 µs symbols, 20 µs symbols and 13 µs symbols are covered in Figures 15, 16 and 17 respectively. Observations of Figures 15 through 17, as well as Table 3, show that the decoder handles the fluctuations of SNR and Doppler well at the lowest data rates (20 µs and 40 µs symbols, BPSK and QPSK) yielding acceptable BER values. The results at the fastest data rate (Figure 17, right) must be used with caution: due to a software issue at the source, only a small fraction of the 13µs-QPSK messages were transmitted, which explains the limited number of messages received. Overall, some messages are severely corrupted, and the BER is higher in the turning basin than in the marina, as shown in Table 2 and 3. This is explained by sudden drops in SNR, due to the rotation of the receiver platform. Because of the short hydrophone cable length at the receiver, the receiver hydrophone was approximately at the same depth as the research vessel keel. As a result, the hydrophone was occasionally shaded, depending on the orientation and roll of the vessel. Overall, Figures 15 to 17 indicate that the link remains fairly reliable despite the fluctuations in Doppler and in SNR.

Upon close observation of Figure 6 (right), one can observe that a message is successfully received despite 300 Hz of Doppler shift. This shows how the decoding algorithm is able to track even large amounts of Doppler, given the SNR remains sufficiently high (20 dB in this case).



Figure 10. Sky view and bathymetry of the south turning basin of Port Everglades, indicating the source and receiver locations (25, 50 and 75 m ranges) and the scope of the source (10 m watch circle) during the experiments of January 2006.
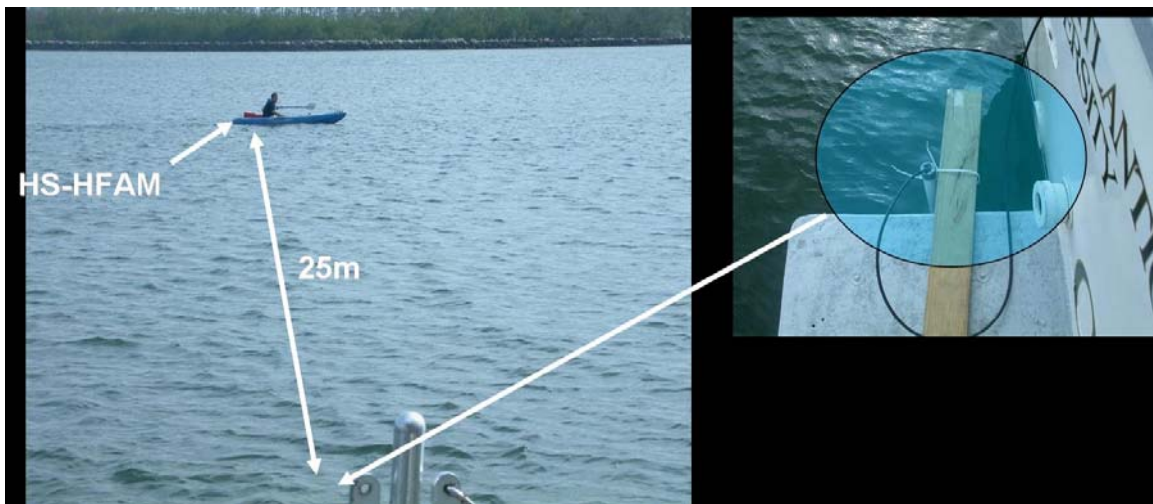
Figure 11.  Boat view of the south turning basin of Port Everglades, indicating the source and receiver locations during the experiments of January 2006.
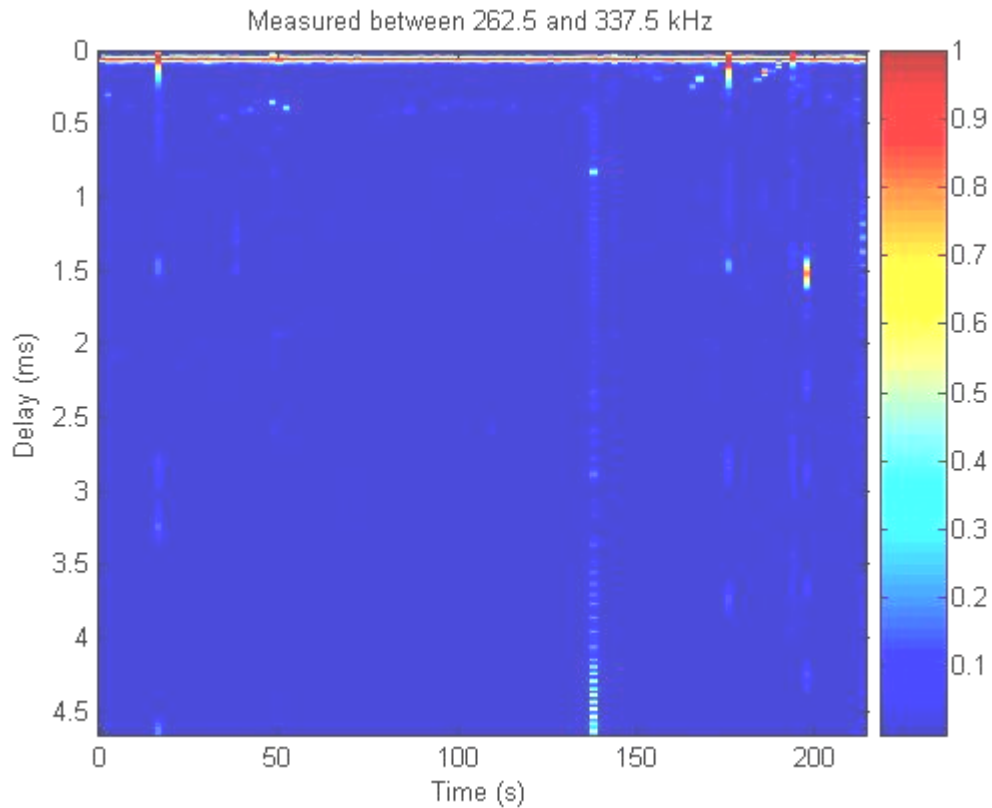


Figure 12.  Impulse response of the acoustic channel when the source is located at 50 m from the receiver, Port Everglades south turning basin, January 25th 2006.
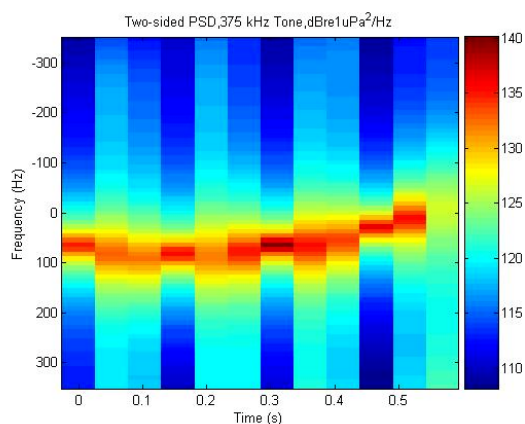
Figure 13. Real-time measurement of the Doppler spread during the transmission of the source is located at 50 m from the receiver, Port Everglades south turning basin, January 25th 2006.
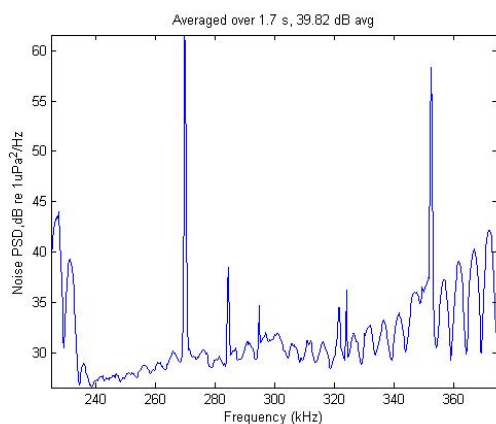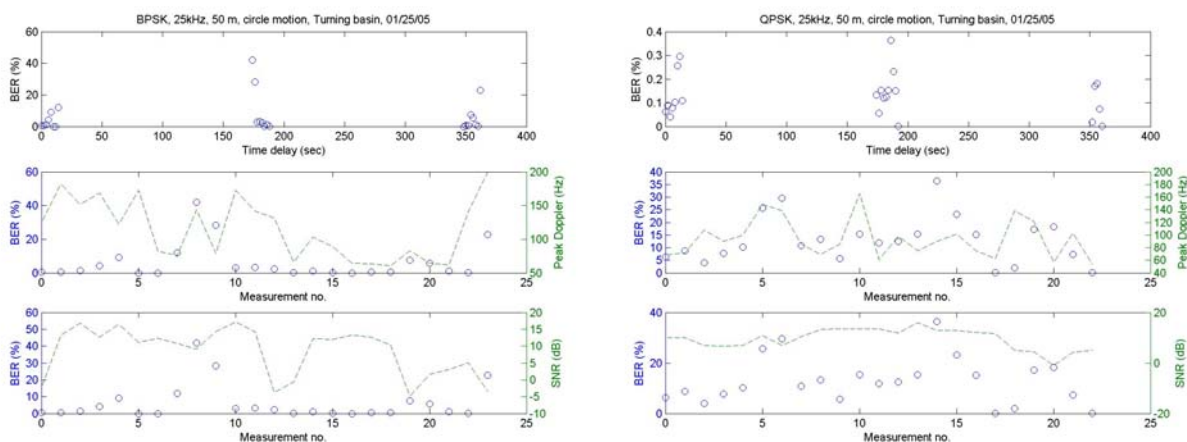


Figure 14. Background noise measurement while the source is located at 50 m from the receiver, Port Everglades south turning basin, January 25th 2006.

Figure 15.  Performance review for messages using 40 µs symbols (BPSK and QPSK), when the source is located at 50 m from the receiver, Port Everglades south turning basin, January 25th 2006.



Figure 16.  Performance review for messages using 20 µs symbols (BPSK and QPSK), when the source is located at 50 m from the receiver, Port Everglades south turning basin, January 25th 2006.
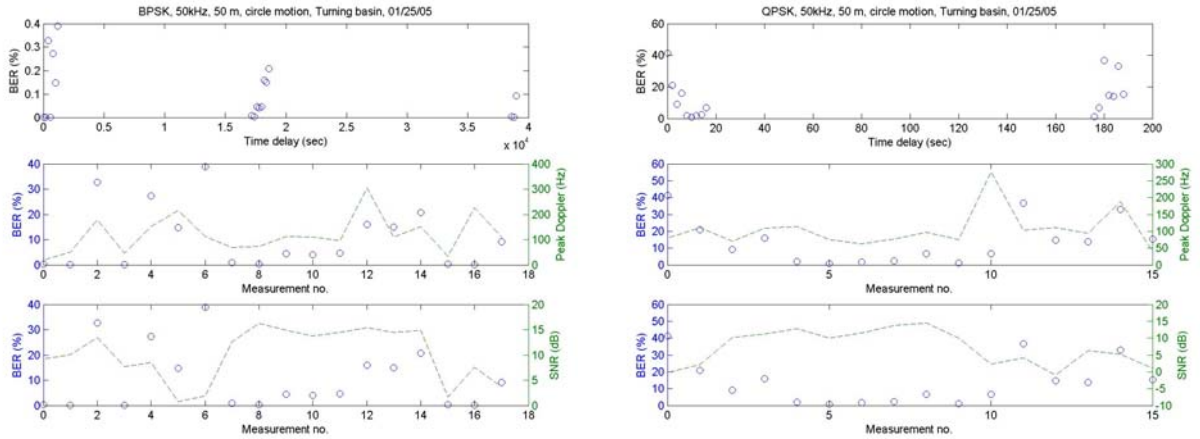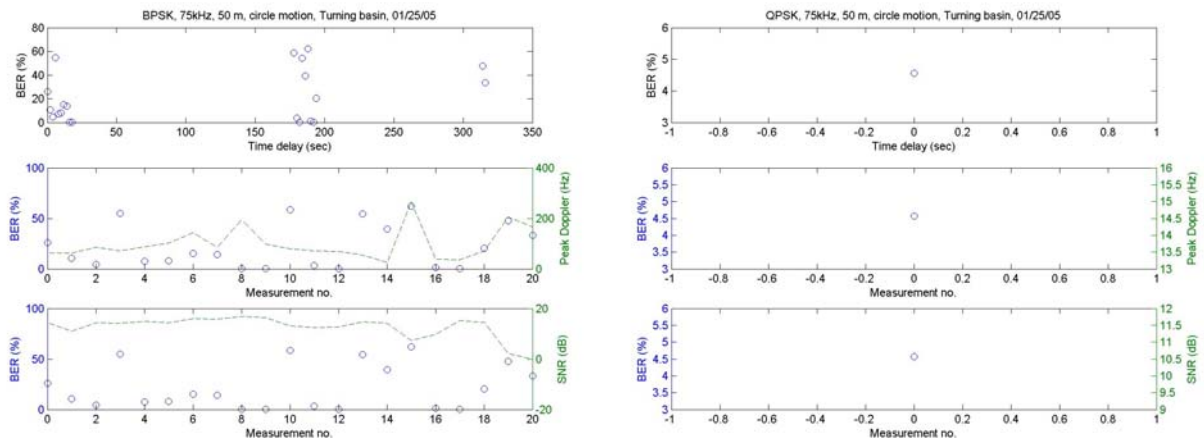


Figure 17.  Performance review for messages using 13 µs symbols (BPSK and QPSK), when the source is located at 50 m from the receiver, Port Everglades south turning basin, January 25th 2006.

## 4.3. Findings

Table 2 and 3 provides a summary of the most significant results obtained during the marina and turning basin experiments, respectively.  For every modulation and symbol length, the BER (minimum, maximum, mean and standard deviation), mean reverberation time and Doppler shift, minimum and maximum SNR and total number of data bits are transmitted.  The percentage of unrecoverable images corresponds to the percentage of messages containing more than 5% of corrupted bits.

Table 2 indicates that, at ranges up to 50 m and under the condition of slow source motion (mean Doppler of approximately 20 to 30 Hz), the BER remains well within 1% at 50,000 coded bps, with the exception of a very limited number of band transmissions. At faster coded rates, the BER starts increasing significantly, but remains fairly acceptable for image transmission up to 100,000 coded bps (3.02% on average at 50 m for QPSK-modulation using 20 µs symbols). 80% to 100% of the received images are likely to be viewable at rates up to 50,000 bps and ranges up to 50m. The performance of the communication system becomes more marginal when 13 µs symbols are used, corresponding to 75,000 and 150,000 coded bps using BPSK and QPSK, respectively. At these rates, messages can be received at a very low BER (0% at 50 m and 75000 bps, 0.09% at 50 m and 150000 bps), while others will occasionally contain an excessive number of corrupted bits (61.12% at 50 m and 75000 bps, 32.07% at 50 m and 150000 bps). Over half the images are likely to be lost at 50 m in this configuration. Again, the results observed at 150,000 coded bps are not accurate, due to the limited number of measurements.

| Modulation Type | BPSK | BPSK | BPSK | QPSK | QPSK | QPSK |
|---|---|---|---|---|---|---|
| Symbol Duration | 40 µs | 20 µs | 13 µs | 40 µs | 20 µs | 13 µs |
| Symbol Bandwidth | 25 kHz | 50 kHz | 75 kHz | 25 kHz | 50 kHz | 75 kHz |
| Source Level (dB re 1uPa^2 at 1m) | 173 | 173 | 173 | 173 | 173 | 173 |
| | | | | | | |
| MARINA, SLOW MOTION, 25 m | | | | | | |
| No. of Messages | 30 | 24 | 21 | 29 | 19 | 6 |
| No. of Data Bits | 245760 | 196608 | 172032 | 237568 | 155648 | 49152 |
| Min SNR (measured at trigger) | 24.2 | 22.4 | 1.8 | 2.3 | 5 | 29.2 |
| Max SNR (measured at trigger) | 33.1 | 33.3 | 33.6 | 35.2 | 32.3 | 33.3 |
| Mean Reverberation time (msec) | 1 | 1 | 1 | 1 | 1 | 1 |
| Mean Doppler measured at 375 kHz (Hz) | 19.69 | 17 | 20 | 19.6 | 21.8 | 8.2 |
| Minimum BER observed for a message (%) | 0.0000% | 0.1460% | 0.5850% | 0.0000% | 1.1200% | 19.9300% |
| Maximum BER observed for a message (%) | 4.7400% | 26.8000% | 53.1200% | 16.4000% | 42.9500% | 52.4400% |
| Mean BER (%) | 0.3470% | 5.7000% | 12.3000% | 2.5000% | 9.9500% | 38.9300% |
| Std dev BER (%) | 0.9500% | 7.5000% | 14.8000% | 4.1100% | 9.5500% | 16.9300% |
| Percentage of unrecoverable images (%) | 0.0000% | 37.0000% | 52.0000% | 21.0000% | 68.0000% | 100.0000% |
| | | | | | | |
| MARINA, SLOW MOTION, 50 m | | | | | | |
| No. of Messages | 18 | 23 | 23 | 17 | 26 | 3 |
| No. of Data Bits | 147456 | 188416 | 188416 | 139264 | 212992 | 24576 |
| Min SNR (measured at trigger) | 0.2 | 4.2 | 3.5 | -4.4 | -0.1 | 16.9 |
| Max SNR (measured at trigger) | 30.2 | 31.9 | 30.4 | 29.3 | 30.2 | 30.8 |
| Mean Reverberation time (msec) | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Mean Doppler measured at 375 kHz (Hz) | 31.3 | 28.83 | 27.4 | 29.2 | 26.8 | 31.1 |
| Minimum BER observed for a message (%) | 0.0000% | 0.0000% | 0.0000% | 0.0000% | 0.0200% | 0.0900% |
| Maximum BER observed for a message (%) | 5.1900% | 1.9900% | 61.1200% | 6.7100% | 49.7300% | 32.0700% |
| Mean BER (%) | 0.3200% | 0.1000% | 23.2500% | 0.4200% | 3.0200% | 11.3000% |
| Std dev BER (%) | 1.2200% | 0.4200% | 25.2800% | 0.0160% | 9.7600% | 17.9800% |
| Percentage of unrecoverable images (%) | 0.0000% | 0.0000% | 52.0000% | 5.0000% | 8.0000% | 33.0000% |

Table 2. Overall performance of the HS-HFAM during the trials in the SeaTech marina at ranges up to 50 m, January 2006.

Table 3 shows that, if the relative motion between the source and the receiver increases, the performance will drop, especially when the data rate is high. Measurements indicate a mean Doppler of approximately 100 Hz at 50 m, as compared with 30 Hz during the tests in the marina

(Table 2). Within a range of 50 m, the BER remains within 5% at 50,000 coded bps and less if BPSK modulation is used. QPSK modulation appears to be more sensitive to rapid fluctuations of Doppler and does not perform as well under these circumstances. Overall, 80% to 85% would most likely be viewable at a range of 50 m or less and at a data rate of 100,000 coded bps or less, if the relative motion does not exceed 1.5 m/s.

The results obtained at 75 m are marginal, as the source level was not sufficient to provide acceptable results. The SNR rarely exceeds 4 dB, which significantly limits the performance of the system. The source motion also induces significant amounts of Doppler in the received data (more than 100 Hz averaged across the measurements). Despite these adverse conditions, the BPSK modulation performs fairly well up to 50,000 coded bps. Measurements show that 60% to 80% of the images could be viewable under these circumstances.

Figure 19 shows an example of the same transmitted image containing a limited number of corrupted bits when decoded. These data were collected at 50 m during the measurements during the marina experiment of January 2006. The selected data rates (100,000 and 150,000 coded bps) are intentionally high, to illustrate a more challenging scenario, and are shown in order of increasing BER. The BER reaches 1.84% when the image is received at 150,000 coded bps, but remains viewable. Overall, despite the presence of incorrect bits, the overall image appearance undergoes little change.
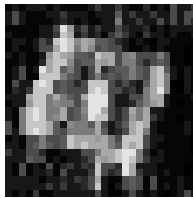


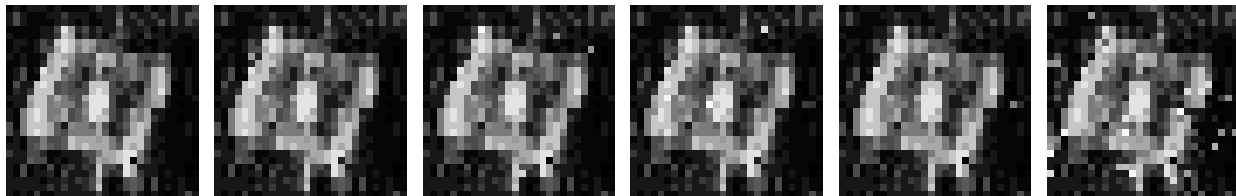Figure 18. Example of an 8192-bit PGM image transmitted during the latest tests (January 2006)



Figure 19. Examples of images collected at 50 m range in the FAU Marina in January 24th 2006. The two right-most images were transmitted at 150,000 coded bps, the others were transmitted at 100,000 coded bps. BER from left to right: 0.024%, 0.098%, 0.293%, 0.366%, 0.854%, 1.843%

| Modulation Type | BPSK | BPSK | BPSK | QPSK | QPSK | QPSK |
|---|---|---|---|---|---|---|
| Symbol Duration | 40 µs | 20 µs | 13 µs | 40 µs | 20 µs | 13 µs |
| Symbol Bandwidth | 25 kHz | 50 kHz | 75 kHz | 25 kHz | 50 kHz | 75 kHz |
| Source Level (dB re 1uPa^2 at 1m) | 173 | 173 | 173 | 173 | 173 | 173 |
| | | | | | | |
| BASIN, SLOW MOTION, 25 m | | | | | | |
| No. of Messages | 27 | 25 | 20 | 35 | 19 | 1 |
| No. of Data Bits | 221184 | 204800 | 163840 | 286720 | 155648 | 8192 |
| Min SNR (measured at trigger) | -13.8 | -5.9 | -2.4 | -1.8 | 1.6 | 7.6 |
| Max SNR (measured at trigger) | 21.7 | 22.7 | 19.5 | 29.4 | 24.8 | 7.6 |
| Mean Reverberation time (msec) | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Mean Doppler measured at 375 kHz (Hz) | 60.84 | 46.85 | 34.37 | 42.19 | 40.8 | 56.7 |
| Minimum BER observed for a message (%) | 0.0000% | 0.0000% | 0.0000% | 0.0000% | 0.0480% | 39.6000% |
| Maximum BER observed for a message (%) | 34.1300% | 7.8200% | 62.9500% | 38.0700% | 27.1800% | 39.6000% |
| Mean BER (%) | 3.5500% | 1.4880% | 24.2800% | 9.7600% | 7.9600% | 39.6000% |
| Std dev BER (%) | 7.3600% | 2.3200% | 27.3900% | 10.6400% | 9.3100% | 0.0000% |
| Percentage of unrecoverable images (%) | 22.0000% | 12.0000% | 45.0000% | 54.0000% | 47.0000% | 100.0000% |
| | | | | | | |
| BASIN, 1.5 MPS SPEED, 50 m | | | | | | |
| No. of Messages | 24 | 18 | 21 | 23 | 16 | 1 |
| No. of Data Bits | 196608 | 147456 | 172032 | 188416 | 131072 | 8192 |
| Min SNR (measured at trigger) | -4.8 | 0.8 | -1 | -1 | -1 | 10.7 |
| Max SNR (measured at trigger) | 17.1 | 16.2 | 16.9 | 16 | 14.5 | 10.7 |
| Mean Reverberation time (msec) | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Mean Doppler measured at 375 kHz (Hz) | 114.35 | 120.43 | 99.03 | 94.2 | 104.9 | 14.6 |
| Minimum BER observed for a message (%) | 0.0000% | 0.0100% | 0.0240% | 0.1400% | 0.7600% | 4.5600% |
| Maximum BER observed for a message (%) | 41.9000% | 38.9400% | 62.1200% | 36.3900% | 41.3000% | 4.5600% |
| Mean BER (%) | 6.0500% | 10.5300% | 21.9700% | 12.9000% | 13.8600% | 4.5600% |
| Std dev BER (%) | 10.5300% | 12.3700% | 22.1300% | 9.2200% | 13.1100% | 0.0000% |
| Percentage of unrecoverable images (%) | 29.0000% | 44.0000% | 66.0000% | 82.0000% | 68.0000% | 0.0000% |
| | | | | | | |
| BASIN, 1.5 MPS, 75 m | | | | | | |
| No. of Messages | 5 | 5 | 10 | 2 | 6 | 0 |
| No. of Data Bits | 40960 | 40960 | 81920 | 16384 | 49152 | 0 |
| Min SNR (measured at trigger) | -5.9 | -2.6 | -1.8 | -4.4 | -1.9 | |
| Max SNR (measured at trigger) | 4.8 | 3.5 | 7.3 | 1.6 | 3.5 | |
| Mean Reverberation time (msec) | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | |
| Mean Doppler measured (Hz) | 163.82 | 151.33 | 155.6 | 77.8 | 86.15 | |
| Minimum BER observed for a message (%) | 0.6500% | 0.1830% | 0.5400% | 0.3900% | 0.9400% | |
| Maximum BER observed for a message (%) | 21.8300% | 9.5200% | 61.3800% | 15.3900% | 37.1600% | |
| Mean BER (%) | 7.3600% | 2.8400% | 20.8000% | 7.8900% | 13.9600% | |
| Std dev BER (%) | 8.5900% | 0.0380% | 17.8200% | 10.6000% | 15.8000% | |
| Percentage of unrecoverable images (%) | 40.0000% | 20.0000% | 90.0000% | 50.0000% | 50.0000% | 100.0000% |

Table 3. Overall performance of the HS-HFAM during the trials in the Port Everglades south turning basin at ranges up to 75 m, January 2006.

| | Marina slow motion | Basin 1.5 mps | Basin slow motion |
|---|---|---|---|
| Max reliable Bits / Joule | 139682 | 93121 | 41904 |
| Max reliable rate tested (coded bps) | 150000 | 100000 | 50000 |
| Max reliable range tested (m) | 50 | 50 | 75 |
| Max reliable coded Range-Rate (kbps-km) | 7.5 | 5 | 3.75 |

Table 4. Performance summary and bit efficiency of the HS-HFAM.

Overall, acoustic communications were made possible at a rate up to 150,000 bps (coded) at a range of 50 m.  At 75 m, acoustic communications was still possible up to 50,000 bps (coded), due to limitations of the source power amplifier.  Accurate Doppler correction is required to perform broadband underwater acoustic communications at high-frequencies, along with a sufficient SNR.  However, results observed at 75 m under adverse conditions in terms of Doppler and SNR (4 dB) indicate that the BPSK modulation still provides acceptable results using 20 µs and 40 µs symbols.

The results listed in Table 2, 3 and 4 are obtained using an omni-directional source of 173 dB (0.63 W of acoustic power), which sets a limit on the range of the HS-HFAM in its current configuration.  This shows, however, that the HS-HFAM is remarkably power efficient.  Table 4 shows the energy efficiency of the fastest transmission modes in bits/J:  93,121 bits/J at 100,000 coded bps and 130,692 bits/J at 150,000 coded bps.  The HS-HFAM is very highly energy efficient and very well suited for small unmanned underwater vehicles and divers with little battery energy to spare.  This should be put in perspective with state-of-the-art spread-spectrum MFSK acoustic modems, whose bit efficiency is traditionally of the order of 10 bits/J at best.

## 5. Conclusions

Through the course of this phase-I work, Five types of experiments have been performed to provide more detailed answers to these questions:
1. Using direct connection between the source and the receiver [9].
2. In the test tank [9].
3. In the marina facing FAU SeaTech, keeping source and receiver static at 40 m range [9]. The water depth was 1 m.
4. In the same marina experiments at ranges from 20 m to 50 m.  These tests took place in December 2005 and January 2006.  The source was either still or moving at a top speed of 1 m/s.  The water depth varied between 1 and 2 m.
5. In the Port Everglades turning basin experiments at ranges from 20 m to 80 m.  Both source and receiver were moving at a top relative speed of approximately 1.5 m/s.

As a conclusion to this 6-month study, the original questions can be answered:
- **Can a bit rate-range product of 50 kbps-km or more be achieved?**
  150,000 coded bps have been transmitted at 50 m, which corresponds to a coded rate-range of 7.5 kbps-km, when the source is in slow motion.  This number drops to 5 kbps-km at a pace of 1.5 m/s.  These results are limited due to SNR, as they have been obtained using a 0.63 W source.  The long term objective is to design and build a more powerful power amplifier to achieve 500 m range.  Under these conditions, a range-rate of 50 kbps-km appears reasonable.
- **What is the efficiency in bits/Joule of this system?**
  The HS-HFAM is extremely power efficient, as it performs high-speed communications at 130,692 bits/J for 150,000 coded bps.  This should be put in perspective with state-of-the-art spread-spectrum MFSK acoustic modems, whose bit efficiency is traditionally of the order of 10 bits/J at best.

- **What is the frame error rate, or number of non-recovered messages, over the course of minutes, hours and days as a function of range, rate and environmental conditions?**

  Over the course of hours, days two consecutive months, the HS-HFAM has proved very reliable, pending the vehicle motion is slow and the range remains within 50 m. Increased vehicle motion keeps the upper limit of performance to a coded rate of 100,000 bps at 50m. Under these conditions, 80% of the transmitted images would be viewable. This series of tests has revealed some limitations in the current Doppler tracking loop algorithm in terms of robustness under rapid fluctuations of velocity. A modified algorithm is currently under development to answer this issue.

- **If proved to work, can this device be in the form of a small, low-power package compatible with modern autonomous underwater vehicles?**

  The HS-HFAM has already been proved to work in a small, very low-power package (Figures 5 and 14). The prototype source DSP and power amplifier combined fit in a 4½-by-8 inches canister and runs on 48 Volts DC. The ITC-1089D transducer is 2 inches long and 0.38 inch in diameter. In the current configuration (source level of 173 dB), the source hardware consumes approximately 1.5 W, including 0.5 W for the electronics and transducer losses. The receiver unit is self-contained in a splash-proof case (Figure 5), while the decoding software runs on a standard Centrino PC laptop connected to the acquisition unit using 802.11g (WiFi).

## 6. Recommendations

The long-term objective of this program is the development, testing and commercialization of a high-speed high-frequency acoustic modem (HS-HFAM) capable of transmitting data at true rates of up to 105,000 bits per second (bps), at a maximum range of 500 meters. This modem will operate between 240 kHz and 360 kHz approximately, and achieve a maximum range-to-true rate in excess of 50 kbps-km. Based on the results and conclusions presented in the two previous sections, it appears that this objective can be achieved.

The results obtained during this Phase-I lead to following list of recommendations to be addressed during the second phase of the STTR:

1. To improve the range of the HS-HFAM with a more powerful power amplifier and transducer. Overall, a dedicated source prototype, comprising an embedded DSP board, power amplifier and transducer, should be designed and built.
2. To improve the robustness of the decoding software to rapid fluctuations of Doppler.
3. To adjust the modulation based on the maximum acceptable BER. Typically, small portions of compressed images are highly error-sensitive, while the bulk of the image shows only limited sensitivity in bit errors.

## 7. References

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